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ULTRAVIOLET DISINFECTION OF POTABLE WATER SUPPLIES

DIVISION OF RESEARCH

ONTARIO WATER RESOURCES COMMISSION

March, 1969 R. P. 2012

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POTABLE WATER SUPPLIES

By:

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March, 1969

Division of Research

Paper No. 2012

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SUMMARY

Based on a literature survey and laboratory tests, this report attempts to present an objective evaluation on the applicability of ultraviolet radiation for water purification. It gives a brief history of the early attempts and the work of recent investigators to utilize ultraviolet sterilization in water treatment. It also describes the mechanism of germicidal action and outlines some of the limitations and other important factors which affect the effectiveness of ultraviolet rays as a sterilizing agent.

Details are given of evaluation tests involving a commercial water purification system developed for the consumer market and designed to disinfect potable water supplies by means of ultraviolet rays. It was tested on both river water and artificially contaminated tap water to assess its treatment efficiency under various operating conditions.

Bacterial examinations of samples of water treated at low flow rates (30 to 40 percent of the design capacity) showed complete inactivation of coliform organisms and viruses, but at the higher flow rates there was an apparent breakthrough of turbidity and the appearance of some live organisms in the treated water.

INTRODUCTION

The germicidal properties of ultraviolet (UV) light have been well known and established for many years. When exposed to UV radiation under proper conditions, most species of bacteria, fungi and viruses can be effectively inactivated whether they are air-borne or suspended in liquids. As a result, UV has been employed as a germicidal agent in a wide range of applications such as in the manufacturing and packaging of numerous beverages, foods and pharmaceutical products; in the sterilization of cutlery, dishes, glassware, instruments and utensils in hospitals, laboratories, restaurants or any place where contamination by air-borne bacteria and human contact is undesirable; in the sanitation of ventilated air for hospitals, nurseries, industrial plants, public buildings, schools and other areas where the spreading of contagious diseases may occur; in the preparation of immunizing antigens; and in the disinfection of water and other liquids whose flavours may be impaired by chemical methods of treatment.

In the past, several attempts have been made to utilize UV for the disinfection of water on large scale applications. Unfortunately, equipment costs, power requirements, operating difficulties and the availability of chlorination had precluded its widespread use for water treatment. With the development of more efficient and low cost UV germicidal lamps, there has been a renewed interest in utilizing UV for purification of small water supplies.

Today, there are several types of UV water purifiers sold commercially. Many of these are designed for use with household water systems and are considered to be ideally suited for purifying water for cottages, farms, summer camps and tourist establishments located in isolated areas. All of these claim to be capable of producing water that will meet the drinking water standards promulgated by public health authorities.

It is the purpose of this report to present a critical review of the information published in the literature with regards to the present status of UV radiation in water purification. Some results of evaluation tests with a commercial UV water purifier system are included.

HISTORICAL BACKGROUND

General

A review of the literature has indicated that the lethal effects of UV light on bacteria and molds have been known for well over ninety years. The first discovery of bactericidal effects of radiant energy of sunlight was recorded by Downes and Blunt in 1877.[1] They observed the lethal effects of sunlight on a mixture of microorganisms found in a dish of putrefying substances. They concluded that the light of short wavelengths was responsible for the destruction of these organisms. Since then, this aspect of radiant energy and particularly UV has been a subject of study for numerous investigators who have demonstrated that its bactericidal property is dependent upon such factors as wavelength, intensity, energy and type of organisms. The details of these studies by the earlier workers have been reviewed and presented by various authors.[1,2,3,4]

Application of UV to Water Purification

According to the literature, the first known attempt to use UV for public water supply was made in 1910 at Marseilles, France where an experimental UV apparatus was set up to treat 158,500 US gpd.[5,6] Similar attempts were believed to be made later in other parts of France and Europe but no records were kept.

At least four municipalities in the United States adopted UV for water treatment during a period dating from 1916 to 1928.[5] The largest waterworks was located at Henderson, Kentucky with a population of 12,000. It had a flow capacity of 2.2 to 3.1 MGD (US). The UV apparatus was installed in 1916 and remained in use until about 1924. Others were reported to be in use at Berea, Ohio during 1923-1936;[1,7] at Horton, Kansas from 1923 but abandoned later and the fourth and the last known US municipal waterworks having a UV installation was at Perrysbury, Ohio during 1928-1939. Brief references have been made to other installations in Central America and Tennessee.[8]

UV water purification devices were employed in ships plying the Great Lakes since 1916 or 1917 and some of these were reportedly to be still in existence as late as 1940. Other installations of UV equipment were made in various parts of the United States for the purification of water supplies serving industrial and related communities, hotels and institutions but many of these were abandoned before 1930.[5]

Some of the reasons given for abandoning UV method of treatment were as follows:

(a) high operating costs in comparison to other methods of disinfection,
(b) more reliable and efficient means of disinfection was made available with the advent of chlorination,
(c) operating difficulties experienced with UV equipment,
(d) maintenance problems.

Development of New Germicidal Lamps

Although the UV method of disinfection failed to gain popularity in water purification and was even abandoned in favour of chlorination in waterworks where it had been in use, research continued and considerable efforts were directed to the application of UV to the destruction of air-borne bacteria and air sanitation. In the meantime, a new tubular type of germicidal lamp was developed from the research that led to the development of fluorescent lamps[9]. Again there was a renewed interest in the application of UV to the disinfection of water.

Luckiesh and his co-workers[10] at General Electric Company examined the practicability and feasibility of utilizing these germicidal lamps in water purification. They studied a number of variables that affected the transmissibility of UV light in different samples of water. They demonstrated with samples of water seeded with B-coli that the degree of disinfection attained was dependent on the intensity of UV radiation which varied with absorption coefficient of water and the distance or depth in the water through which the UV was transmitted.

In another study, Luckiesh and his collaborators[11] developed a method to measure the transmission and absorption of UV light in samples of tap water derived from nineteen US cities. They noted that there was a wide variation in the transmissibility of UV in these samples. In addition, they found that most compounds of calcium, magnesium, sodium and aluminum did not have any appreciable effects in reducing the penetration of UV light but the presence of iron even in small quantities affected it. From the measurement of the transmission characteristics, they were able to calculate the approximate degree of disinfection efficiency that could be expected in the water when subjected to UV irradiation in an efficient water disinfecting apparatus.

The data obtained in these studies were helpful in providing practical design criteria for water disinfecting devices. The basic principles and design requirements for these devices are discussed elsewhere.[4,9,10,12,13]

In spite of these new and more efficient UV germicidal lamps and more sophisticated equipment, a report issued in 1948 stated that the Council on Physical Medicine was not fully convinced of the efficacy of UV as a method of disinfection and considered it as not being completely reliable for the purification of public water supplies.[13]

Evaluation of UV Water Purifiers

The new germicidal lamps provided a more efficient source of UV radiation with greater penetrative power. Various water purification devices employing these lamps were developed commercially for use in swimming pools and small individual water supplies. These commercial units became a subject of interest for a number of workers who have studied their limitations and applications in water treatment under various test conditions.

Gilcreas and De Lalla[14] conducted experiments on a commercial unit (750 gph capacity) to determine some of the limiting values of colour, turbidity and other substances in the water that may interfere with the bactericidal effectiveness of UV being used for disinfection purposes. Similar studies were carried out recently by Huff and his associates (15) to consider some of the factors affecting UV transmission and treatment efficiency in a UV water disinfecting system designed primarily for use on ships. Using samples of heavily contaminated water derived from rural wells, Ricks and his co-workers[16] undertook a systematic study to evaluate various factors which affect the intensity of UV radiation and hence bactericidal efficiency. Cortelyou and his associates[17,18] investigated some of the physical factors that can affect the germicidal efficiency of UV on certain bacteria in water. They also presented some data to show that the germicidal efficiency was related to the intensity of UV radiation.

A few cases have been cited in the literature of commercial UV water purifiers having been tried experimentally on artificially contaminated waters and producing satisfactory results. In one instance, a favourable evaluation report led to some field tests with UV equipment on the treatment of a surface water supply serving a public school in British Columbia[19]. Initially, some difficulties were experienced. Due to the lack of filters, suspended material in the raw water caused a build-up of brownish coloured organic residue on the lamps, thereby reducing the intensity of UV. This problem was cleared up by installating a sand and gravel filter and a carbon filter. This removed the suspended matter and helped to improve the clarity of water. Eventually, the sand and gravel filter was removed with no deterioration of colour and clarity. After two and one-half years of testing, it was concluded that a system consisting of a carbon filter and UV equipment would be a satisfactory method of water treatment for small water supplies.

Faced with the problems of objectionable taste and odours occurring in the water after chlorination, Jepson[20] installed a commercial UV treatment apparatus and found that it gave satisfactory services.

A review of the scientific literature related to water and wastewater practices in the Soviet Union indicates that there has been considerable interest in the application of UV for this purpose. This is discussed below in more detail.

In addition to the disinfection of potable water supplies, UV irradiation has been tried experimentally for the purification of waters used for other purposes.

Fredette[21] reported on his attempts with UV irradiation to prevent a build-up of bacteria in the water circulating in the air ventilation system of a hospital.

Kelly[22] investigated the applicability of UV water purification devices for the disinfection of sea water required for laboratory studies on shellfish. He reported that these units could be operated with a high degree of dependability producing water of acceptable sanitary quality from polluted sea water.

Stratford[23] found that a commercial water sterilizer (40 gph capacity) could destroy various microorganisms with an efficiency of 99.99 percent in highly contaminated test waters with bacterial populations in the order of 10^4 per ml. However, he was somewhat hesitant in recommending UV irradiated waters for use in delicate surgical operations.

Use of UV Treatment in the Soviet Union

The use of UV treatment for the disinfection of domestic water and wastewater has been given serious attention in the Soviet Union.[24,25] Until recently, it was not considered practical in view of its high costs, however, with the development of new technology and new sources of UV radiation, the Russian scientists have been conducting some intensive research in this field. Besides the numerous advantages offered, they have stated that in some applications the actual cost of UV is no higher than that for chlorination. In waterworks utilizing groundwaters or spring water as a source of supply, they claimed that the cost of sterilization by UV is only about one-half to one-third of that for chlorination.

In another study, it was reported that a complete sterilization was achieved in a highly coloured water when treated in a special apparatus equipped with an ultrasonic device and UV germicidal lamps. The test sample obtained from a heavily contaminated river had bacterial counts of 2,500 per 100 ml. After treatment with high frequency vibrations and UV irradiation, the water was said to be acceptable for drinking purposes[26].

Previous Studies by the OWRC

Some preliminary tests were conducted by OWRC staff in 1965 to evaluate the performance of another commercial UV water purifier unit. The source of UV consisted of a germicidal lamp housed on a horizontal box and the water was irradiated as it flowed through. It was designed to handle flow rates up to 900 gph.

The test water was drawn from the Humber River and clarified by diatomite filtration. Laboratory analyses on filtered samples prior to UV treatment indicated turbidities in the range of 0.4 to 4.0 ppm SiO_2* and total plate counts of $20^{\circ}C$ of 67,000 to 240,000 per 100 ml.

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* measured with Hellige Turbidimeter

A review of the compiled data has revealed that the unit effectively destroyed up to 99.9 percent of the organisms in the water at rates varying from 100 to 1,500 gph. Nonetheless, the results of these tests did show that none of the treated samples was completely sterilized even though the water of reasonably good clarity was irradiated with UV for a much longer period of time.

Inactivation of Viruses by UV Radiation

Perhaps, one of the most interesting aspects of UV radiation is its effectiveness in virus inactivation. Several research workers have reported that many species of viruses and vaccines including "enteric" viruses in liquid suspensions can be effectively destroyed with UV radiation. Oppenheimer and his co-workers[27] were able to show that viruses and bacteria in water and biological fluid preparations could be inactivated with UV. Huff and his associates[15] demonstrated that it was possible to achieve complete inactivation of viruses in a commercial UV water purifier operated at maximum flow rates and with less than half of the recommended intensity of radiation. However, when the level of virus population increased beyond 10^4 per ml or when the water was artificially coloured with tea, they found that the effectiveness of UV began to diminish slightly.

Gilcreas and Kelly[28] reported that certain types of intestinal viruses were more susceptible to UV irradiation than the coliforms bacteria. They found that short exposures of UV were more lethal to some species of viruses than they were to coliform. Even with high counts of 10^3 to 10^6 per ml, it was said to be possible to inactivate completely all of the bacteriophages with a 15-second exposure. Vajdic[29] stated that bacteriophages of E-coli B could be more readily destroyed with a short exposure to UV irradiation rather than with chlorination involving 10 ppm chlorine residual and a contact period of 15 minutes.

With the emphasis and greater need for the control of virus transmission, the general consensus is that UV irradiation may offer some interesting possibilities for virus removal in potable water supplies.

PRINCIPLES OF ULTRAVIOLET STERILIZATION

What is Ultraviolet Light?

The term "ultraviolet light" or simply "ultraviolet" is applied to electromagnetic radiations emitted from the region of the spectrum lying beyond the visible light. The range of wavelengths for UV light extends from about 150 Å to 4,000 Å as shown in Figure 1 (Å represents Angstrom Units and is a unit of length equivalent to 10^{-8} cm for measuring the wavelengths of electromagnetic radiations).

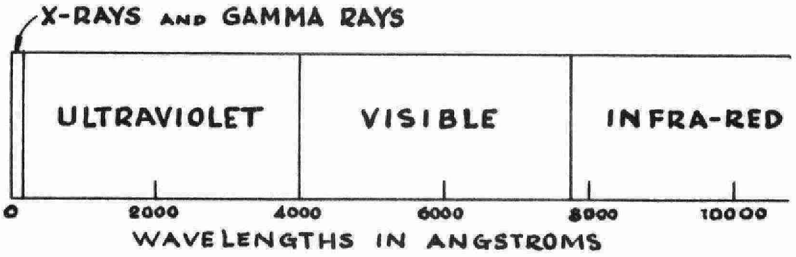

Figure 1

Electromagnetic Spectrum

Sources of UV Light

The sun is one important source of UV light, but much of its transmitted energy does not extend below the wavelength of 2950 Å. For practical applications, UV energy must be generated from special germicidal lamps which are essentially low pressure mercury vapour lamps and it is emitted as a result of an electron flow between the electrodes through the ionized mercury vapour.

Germicidal lamps operate electrically on the same basic principles as the fluorescent lamps. If they are of corresponding size and wattages, they can both produce the same type of UV energy. The difference between the two is that the bulb of the fluorescent lamp is coated with a phosphor compound which converts UV to visible light. The germicidal lamp is constructed of a special quartz glass which is capable of transmitting UV light.

The low pressure mercury vapour lamps have been selected as the most practical source of UV energy. Approximately 60 percent of the input of electrical energy is converted into UV energy with the wavelength of 2,537 Å. It is estimated that UV light at this wavelength produces about 85 percent of the maximum germicidal effect.[3,9]

Mechanism of Germicidal Action

The wavelengths of UV radiation is from 150 Å to 4,000 Å in the spectrum (see Figure 1) but the narrow band lying between 2,000 Å and 3,100 Å has been often called the "abiotic" region because the UV of these wavelengths has injurious and lethal effects on microorganisms including protozoa, fungi, bacteria and viruses. Extensive research has been carried out on this aspect of UV by many workers in an attempt to establish a relationship of intensity, wavelength, type of microorganisms and other factors to the bactericidal effects of UV radiation. The findings and details of these investigations have been reviewed by Ellis[1], Reddish[2] and Huff et al.[15]

Many investigators have found that maximum lethal effects are exhibited when the wavelength of UV is at about 2,650 Å and then declines very abruptly at 2,900 to 3,000 Å with a gradual decrease as the UV wavelength approaches the regions of the visible light. This is illustrated in Figure 2.

Similar to the photographic effect of light, the germicidal action of UV results from its exposure or direct contact with the organism rather than through the formation of a toxic substance in the medium.[9,10] Therefore, this action can be described as being physical rather than chemical.[30] Shechmeister[2,3] suggested that the killing action or the inactivation of the microorganisms due to the exposure of UV, can be expressed as the product of intensity and time as in the following equation: $K = It$

where K = Killing Action
I = intensity of UV light
t = time

From this equation, it can be seen that same exposure can be obtained by using high intensity for a short time or low intensity for a proportionally longer period of time.

The lethal effect is believed to be caused by the absorption of UV energy by various organic molecular components that are essential to the functioning of the cells in the microorganisms. Upon contact, it causes a disruption to the nucleoprotein components and this produces a progressive lethal biochemical change which eventually inactivates and destroys the microorganisms.[15, 27]

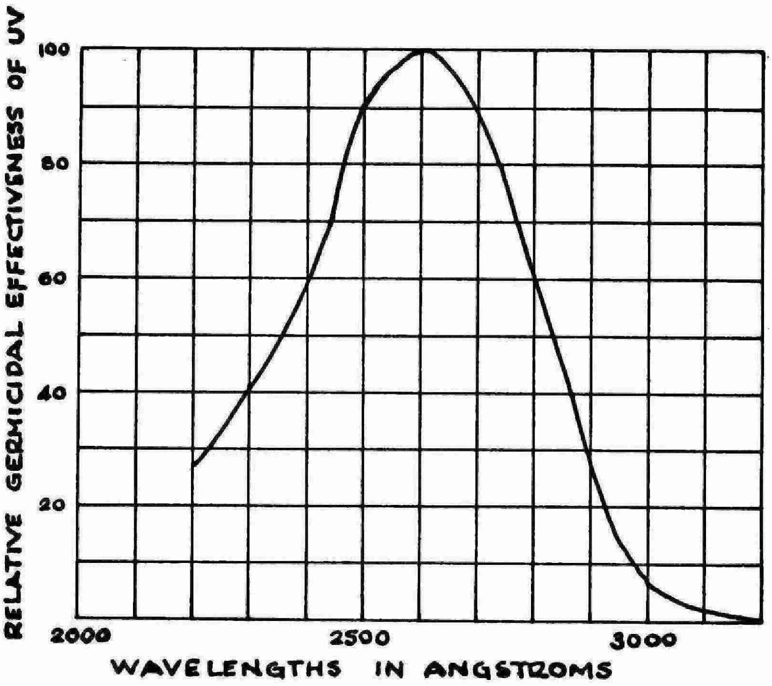

Figure 2

Curve Showing the Relative Bactericidal Effectiveness
of Ultraviolet Radiation
(from General Electric Technical Publication LS-179)

Some Features of UV Application for Water Purification

Several important benefits can be realized from the use of UV in the disinfection of water having good clarity. There are also several limitations and problems that must be resolved before UV disinfection can be considered economically feasible and practical to compete successfully with chlorination, especially in large waterworks. Some of the advantages and disadvantages of UV application in water purification are outlined below.

Advantages

(a) No adjustments are necessary once the UV equipment has been set up.
(b) No danger of overtreatment.
(c) No change in chemical quality of water.
(d) No adverse effects on the palatability of water.
(e) Handling of hazardous and messy chemicals is eliminated.
(f) Under suitable conditions, the killing action on micro-organisms is very rapid and almost instantaneous.
(g) Water of acceptable sanitary quality can be produced without the addition of chemicals.

Disadvantages

(a) Operation costs are more expensive than chlorination.
(b) UV equipment and replacement parts are very costly.
(c) Effectiveness of disinfection depends on direct contact with the organisms and therefore the water to be treated must be free from any colour, turbidity and other substances which interfere with the transmission of UV light.
(d) No residual effect to control or inactivate organisms introduced into the water after the initial treatment.

(e) No simple and reliable field test to check water for adequacy of treatment.

(f) Penetration or transmission of UV light through water depends on chemical quality and may vary from one water supply to another.

(g) Effectiveness of disinfection depends on the intensity of UV output from a germicidal lamp and is governed by primary voltage, water temperatures and length of time that the lamp has been in service.

Factors Influencing Germicidal Efficiency

It is well recognized that water must be reasonably free from colour, turbidity and any other substances that may interfere with the penetration or transmission of UV energy before it can be disinfected satisfactorily. In addition, there are several other factors which can also affect UV radiation and its intensity and thus exert some influence on its germicidal efficiency.

In reviewing the work of numerous investigators[14,16,17,18] some of these factors can be classified into two broad categories:

(a) those affecting the available intensity of UV,

(b) those affecting the application of the available intensity of UV.

(a) Factors Affecting Available Intensity of UV

(i) Lamp Conditions

This refers to the burning age of the lamp. When a germicidal lamp has been in service for any length of time, its output of UV decreases very rapidly during the first 100 hours of operation and then depreciates gradually, thus diminishing its germicidal effectiveness. In order to insure adequate disinfection, the use of a germicidal wattmeter is suggested for direct measurements of UV output in applications where large numbers of lamps are used. For water purifiers, it is recommended that the lamps should be changed after six months of continuous use.[12,16]

(ii) Power Line Voltage

Data presented by Cortelyou and his co-workers[18] showed that a drop in the line voltage may bring a significant decrease in the intensity of UV emitted by the germicidal lamp.

(iii) Temperature

Temperature is another important factor that can affect the output of UV from the germicidal lamp. It has been shown that when a UV lamp is immersed in cold water there is a marked effect on its UV output. However, with the use of a quartz enclosure to isolate the lamp from direct contact with water, the adverse effects of low temperatures on UV output can be lessened. Cortelyou et al[18] showed that an average UV output of a lamp immersed in cold waters with temperatures of 10 to 0°C will drop very sharply to approximately 58 to 22 percent of its actual output in water at 20°C. By comparison with the use of a quartz enclosure, an average UV output of a lamp submerged into waters of same temperature is about 98 to 74 percent of its actual output at 20°C.

(iv) Characteristics of Water

The germicidal effectiveness of UV is dependent upon its contact with the microorganisms in water. According to the work of Luckiesh, Taylor and Kerr[11] and later by Hoather[31], it was demonstrated that the rate of disinfection was dependent on so-called transmission factors or penetrative ability of UV in the water. The latter is related to its absorption coefficient, an inherent characteristic of water which is governed by the presence of dissolved constituents.

(b) Factors Affecting the Application of Available UV

(i) Sensitivity of Microorganisms to UV

Several factors influence the sensitivity of bacteria to UV. Schechmeister[2,3] considers the following as some of the more important factors:

(1) pH,
(2) different stages of bacterial growth cycle, with the greatest sensitivity being in the logarithmic growth phase,
(3) presence of spores which are about twice as resistant as vegetable cells.

It is apparent that some bacteria are more resistant to UV than others. Some data related to the amount of UV energy needed to inactivate some of the common microorganisms have been compiled by Nagy.[32] One of the least resistant species is mentioned to be Salmonella typhosa[18] while a number of authors[2,3,15] reported that E-coli, an indicator organism for fecal pollution shows a greater resistance than any of the water-borne enteric pathogens to UV radiation. However, algae, spores and vegetative cells of many fungi are more resistant than E-coli. It has been suggested that E-coli would be an appropriate organism to establish the minimum standard for a UV water purifier.[15,28]

(ii) Length of Exposure

The time required for the inactivation of microorganisms depends on the intensity of UV, distance from the source of illumination and the nature of the medium in which organisms are exposed. However, it is generally agreed that the bactericidal action is practically instantaneous and the total effect may take place at the moment when the UV rays impinge on the organism.[14] In clear water, if the UV source is placed within 12 inches of the water, 4 seconds is considered to be sufficient time of exposure.

(iii) Operation and Maintenance of Lamps

Improper operating procedures and poor maintenance practices may adversely affect the germicidal efficiency of these units. Continuous operation of the germicidal lamp is considered desirable because this would permit the water passing through the unit to be exposed to UV irradiation at all times. The glass enclosure of the germicidal lamp may become covered with deposits of film and other extraneous substances which may obscure and shield the organisms from UV light.[12,16]

EXPERIMENTAL DETAILS

Description of the Test Equipment

The tests to assess the effectiveness of UV treatment were performed on a UV water purification system manufactured and sold by Aquacare Water Purifiers Limited for household use. Basically, it consisted of an auxiliary carbon filter and a UV sterilizer unit. The carbon filter, a Model AC-10 was similar in design to a household water softener, but filled with granular activated carbon supported on a gravel bed and equipped with a backwashing system. The UV sterilizer, a Model 300, shown schematically in Figure 3, consisted of one G36T6 UV germicidal lamp fitted into a 3-inch diameter schedule 80 plastic pipe to form an annular passage through which the water flowed while being irradiated. Its flow capacity was stated to be 500 gph. Additional data are presented in Table I.

One of the unique features of this apparatus was its automatic safety control system. This consisted of a UV sensitive photocell which was positioned on the outside of the UV sterilizer unit to monitor the intensity of radiation that penetrated through the water. Under normal operating conditions, the cell activated a solenoid valve which allowed the passage of water through the unit. In the event of an electrical failure, or if the UV light of predetermined intensity, failed to penetrate the water due to excessive turbidity, it deactivated the solenoid valve to shut off the water supply.

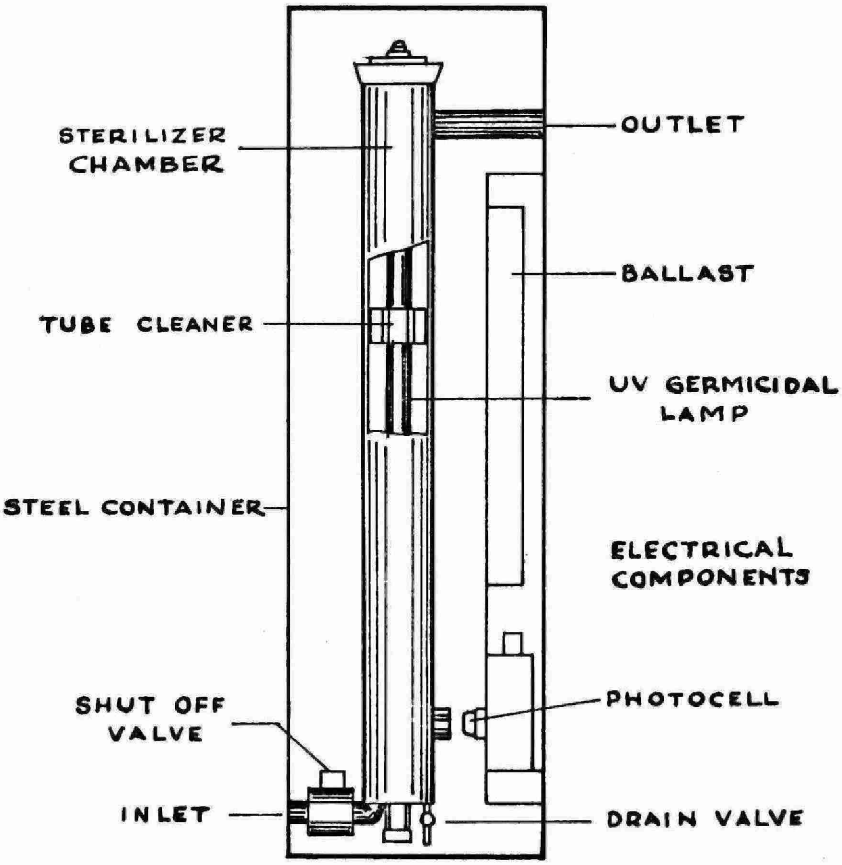

Figure 3

Schematic Diagram of UV Sterilizer

Aquacare Model 300

Table I

ESTIMATED RETENTION TIMES IN UV STERILIZER

Rate of Flow		Retention Time
gpm	% of design	in seconds
1.0	12	43.5
1.5	18	29.0
2.0	24	21.0
2.5	30	17.4
3.0	36	14.5
4.0	48	10.9
5.0	60	8.7
6.0	72	7.3
6.5	78	6.7
7.0	84	6.2
8.0	96	5.4

The above data were calculated from the following assumptions:

Design Flow Rate - 500 gal per hr
- 8.33 gal per min

Dimensions of UV Sterilizer Chamber
inside diameter of plastic pipe - 3 in.
length of plastic pipe - 32 in.
outer diameter of germicidal tube - 1 in.

The unit was also equipped with a patented tube cleaner. This was a plastic collar encircling the germicidal tube which moved up and down with the differential water pressures in the chamber. This moving action helped to prevent the build-up of residue being deposited on the tube. The formation of the residue was considered undesirable because it had a tendency to reduce the UV radiation and adversely affect the germicidal efficiency of the lamp.

Figure 4 shows a schematic diagram of the general layout for the pilot unit used in this study.

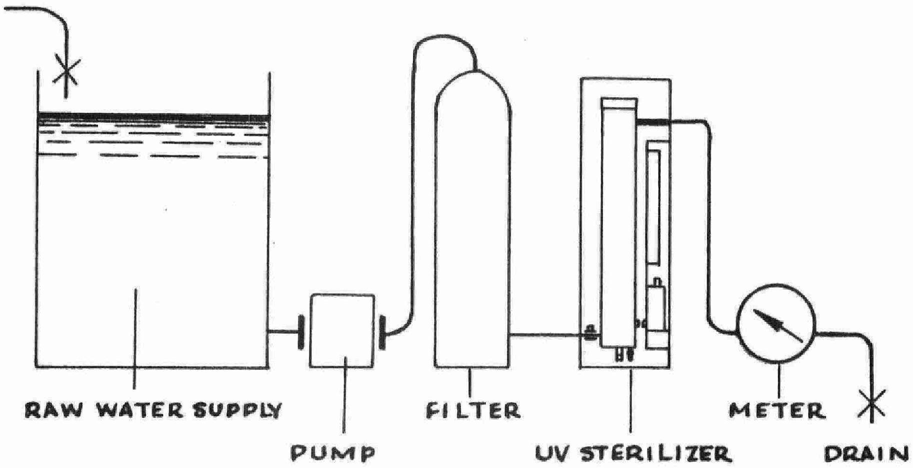

Figure 4
Schematic Diagram Showing the General Layout
of the Equipment for These Experiments

Test Procedures

The evaluation of this system was conducted with experiments on natural surface water and artificially contaminated tap water. The surface water was drawn from the Humber River and the tests were designed to evaluate the performance of the unit in the purification of water subjected to wide range of seasonal water quality and temperature changes. The contaminated water was made up by mixing thoroughly tap water with a small volume offresh domestic sewage in a large holding tank prior to UV treatment. Brewed tea and iron chloride solution were used to impart colour to the water as required.

Prior to UV irradiation, the water was filtered in nearly all of the tests to remove turbidity and clarify it as much as possible.

During the experiments, the test water was pumped through the unit at predetermined flow rates. The efficiency of disinfection was determined by the bacterial examination of the irradiated samples in accordance with the procedures prescribed in Standard Methods (33).

Samples were collected at frequent intervals for pertinent chemical and physical analyses to assess conditions of water quality.

Virological Studies

For tests to determine the efficiency of UV treatment on the inactivation of viruses, 500 gal of tap water was seeded with a culture of E-coli bacteriophages and then pumped through the UV water purifier at varying flow rates. In some tests, the water was artificially coloured with brewed tea prior to UV irradiation. The population of the viruses were enumerated by the most probable number technique described by Vajdic.[34]

Virus studies were also conducted on the water obtained from the Humber River.

EXPERIMENTAL DATA AND OBSERVATIONS

Test Results

All of the data collected from the 14 test runs with the system are summarized in Tables 2, 3, 4 and 5. These include information related to water quality conditions, levels of bacterial and virus populations in the samples before and after treatment and the flow rates through the unit.

Observations

These are a few comments and observations recorded during this investigation:

1. It should be noted that the unit was subjected to evaluation tests involving treatment and purification of waters with much higher levels of contamination than the waters usually considered for potable uses.

2. Information presented in the brochure supplied with the unit indicated that it was designed to handle flows up to 500 gph. With the particular pump used during this investigation, the maximum throughput was found to be approximately 78 to 80 percent of stated capacity.

3. Occasionally the water in the Humber River was highly turbid with turbidity readings in the range of 60 to 100 ppm SiO_2. Although the filter supplied with the unit did remove much of the turbidity to the levels of 20 to 30 ppm SiO_2, the clarity in the filtered water would not be considered aesthetically attractive.

4. At higher flow rates, there was some breakthrough of turbid water in the filtered water. This was evident by the gradually increasing turbidities.

5. The automatic safety control device did take effect and shut off the flow of water whenever the turbidity reached over 35 ppm SiO_2 This usually happened when the flow rates were increased to above 3.5 gpm. The flow of water would stop occasionally at flow rates above 4.0 gpm even though the turbidity was less than 30 ppm SiO_2.

6. It was evident from the bacteriological results that there was no appreciable lessening of the effects of the UV light resulting from tests conducted on cold waters with temperatures below 5.0°C.

Table II

SUMMARY OF RESULTS - EXPERIMENTS WITH TAP WATER

Run No.	Date	Water Analysis				Before UV Treatment			Flow Rate GPM	After UV Treatment			Remarks
		Colour	Turbidity	Iron	Temp. °C	Coliform	Fecal	Strepto		Coliform	Fecal	Strepto	
1-1	Jul 23/68	< 5	<1.0	0.2	25	0	0	0	5.0	0	0	0	
4-1	Aug 7/68	< 5	5.5	0.3	15	27,000	6,100	> 300	1.5	0	<4	0	Tap water mixed with domestic sewage
4-2		-	-	-	-	20,000	3,500	> 300	2.0	0	0	0	
4-3	Aug 8/68	< 5	4.3	-	15	110,000	99,000	-	4.0	8	8	-	
7-1	Aug 21/68	90	15	2.75	17	830	164	456	1.5	<4	<4	<4	Tap water mixed with domestic sewage and ferric chloride solution
7-2		< 5	0.5	0.11	-	1,000	72	<4	2.0	<4	<4	<4	
7-3		> 100	15	3.0	-	1,160	328	252	3.0	36	8	<4	
7-4		> 100	15	-	-	810	320	228	6.5	188	64	16	

Notes: (1) Nearly all water analyses were performed on samples of water collected after UV treatment.

(2) Colour is measured in Hazen units; turbidity in ppm SiO_2; and iron in ppm Fe.

(3) Bacterial results are expressed in counts per 100 ml and they were determined by the membrane filter technique.

(4) "Strepto" refers to Fecal Streptococci which is used sometimes as indicator organisms to measure the degree of pollution from human and warm-blooded excreta.

(5) In Run No. 7, the test water was irradiated directly without filtration. Filtered water was used only in Run 7-2.

Table III

SUMMARY OF TEST DATA - EXPERIMENTS WITH HUMBER RIVER WATER

		Water Analyses				Before UV Treatment				After UV Treatment			
Run No.	Date	Colour	Turbidity	Iron	Temp. °C	Coliform	Fecal	Strepto	Flow Rate GPM	Coliform	Fecal	Strepto	Remarks
2-1	Jul 31/68	10	9.5	0.4	19.0	220	20	-	5.0	<4	<4	-	
2-2		10	12.5	-	18.0	113	60	-	5.2	80	0	-	
3-1	Aug 1/68	10	3.4	1.3	22.0	630	76	-	2.5	<4	<4	-	
5-1	Aug 14/68	30	30	1.2	20.8	740	440	324	2.5	20	4	0	intermittent operation
5-2		35	30	1.6	-	450	260	360	5.0	16	4	4	
5-3		40	60	1.6	-	560	610	310	6.0	16	0	4	
6-2	Aug 19/68	5	5.4	0.7	19.0	140	20	52	2.5	4	12	4	
11-1	Dec 9/68	25	26	1.85	4.2	92	24	-	1.0	0	<4	-	colour was added
11-2		-	25	-	4.2	128	84	-	2.0	0	<4	-	
11-3		40	28	-	3.5	144	144	-	3.0	0	2	-	
11-4		40	32.5	-	3.0	208	198	-	5.4	14	12	-	
11-5		35	11.5	0.5	-	50	44	-	1.5	0	0	-	
11-6		100	38.5	0.7	-	58	52	-	4.4	6	4	-	
11-7		100	-	-	3.0	-	-	-	5.3	32	10	-	
12-1	Dec 11/68	15	22	1.8	3.0	10	4	-	1.0	0	0	-	colour was added
12-2		-	25	-	3.5	78	14	-	2.0	0	0	-	
12-3		-	27	-	-	80	26	-	4.0	0	2	-	
12-4		-	35	-	-	178	40	-	5.3	2	0	-	
12-5		45	30	-	4.0	52	20	-	1.0	0	0	-	
12-6		-	30	-	-	86	16	-	2.0	0	0	-	
12-7		45	35	-	3.5	-	-	-	4.2	0	0	-	

Table III - cont'd

13-1	Dec 18/68	10	12.5	-	4.0	140	56	-	2.0	0	<4	-	
13-2		-	15	-	3.8	-	-	-	3.0	0	<4	-	filter was by-passed
13-3		-	22	-	3.5	-	-	-	4.0	4	4	-	
13-4		15	26	-	3.0	120	136	-	5.0	14	12	-	
13-5		-	38	-	3.0	-	-	-	6.5	88	28	-	
14-1	Jan 6/69	10	20	-	1.8	124	52	-	2.0	0	0	-	
14-2		-	20	-	1.4	-	-	-	3.0	0	0	-	
14-3		-	-	-	1.5	-	-	-	4.0	0	0	-	filter was by-passed
14-4		-	27	-	2.0	280	112	-	5.0	0	2	-	
14-5		-	27	-	-	-	-	-	6.0	0	0	-	
14-6		-	27	-	2.0	-	-	-	6.5	4	0		

Table IV

SUMMARY OF BACTERIOLOGICAL RESULTS

Run No.	Test Water	Temp. °C	Turbidity	GPM	Total Plate Counts at 20°C, per 100 ml		
					Untreated	Treated	% Kill
1-1	Tap water	25.0	1.0	5.0	1.5×10^6	1,520	99.90
2-2	River water	18.0	12.5	5.2	3.3×10^5	2,100	99.36
4-1	Tap water with sewage	15.0	5.5	1.5	2.0×10^6	1,800	99.91
4-2		-	-	2.8	1.5×10^6	1,340	99.91
7-1	Tap water with sewage and $FeCl_3$	17.0	15.0	1.5	-	8,900	91.40*
7-2		-	-	2.0	1.05×10^5	3,000	97.14
7-3		-	-	3.0	1.02×10^5	200	99.80
7-4				6.5	-	6,100	94.11*
11-1	River water	4.2	26	1.5	2.8×10^4	50	99.99*
11-2		-	25	2.0	-	3,600	88.20*
11-3		3.5	28	3.0	3.3×10^4	1,070	96.76
12-1	River water	3.0	22	1.0	2.0×10^5	20	99.99
12-2		3.5	25	2.0	2.6×10^5	1,400	99.46
12-3		-	27	3.0	4.7×10^5	-	-
12-4		-	35	4.0	5.1×10^5	5,600	98.90
12-5	colour added	4.0	30	1.0	2.6×10^5	110	99.96
12-6		-	30	2.0	3.3×10^6	2,100	99.36
12-7		-	35	4.2	-	15,000	-
14-1	River water	1.8	20	2.0	7.9×10^5	200	99.97
14-2		1.4	20	3.0	-	900	99.88*
14-3		1.5	-	4.0	-	1,100	99.85*
14-4		2.0	25	5.0	7.6×10^5	1,800	99.76
14-5		2.0	27	6.0	-	2,600	99.66*

* Calculation based on average results in the untreated sample.

Table V

SUMMARY OF TEST DATA

VIROLOGICAL STUDIES WITH A UV WATER PURIFIER

Run No.	Date	Colour	Turbidity	Temp. °C	Flow Rate gpm	No. of Virus per 100 ml	
						Raw water	Treated water
Tests with Tap Water							
8	Oct 1/68	5	3.5	13		n.d.**	
9-1	Oct 9/68	5	5.8	15	1.6	2 X10^6	n.d.
9-2		-	-	-	3.0	-	2
9-3		-	-	-	5.0	-	23
9-4		100*	6.5	15	1.5	2 X10^6	n.d.
9-5		-*	-	-	3.0	-	5
9-6		-*	-	-	5.0	-	46
10-1	Oct 16/68	5	4.0	17	1.5	3.5X10^6	n.d.
10-2		-	-	-	3.0	-	2
10-3		-	-	-	5.8	-	8
10-4		80*	4.5	19	1.5	2.3X10^6	n.d.
10-5		-*	-	-	3.0	-	5
10-6		-*	-	-	5.8	-	79
Tests with Humber River Water							
11-2	Dec 9/68	25	26	4.2	2.0	175	n.d.
11-3		-	-	-	3.0	-	n.d.
11-4		-	-	-	5.4	-	n.d.
13-1	Dec 18/68	10	12.5	4.0	2.0	221	n.d.
13-2		-	15	3.8	3.0	-	n.d.
13-3		10	22	3.5	4.0	-	n.d.
13-4		-	26	3.0	5.0	-	n.d.
13-5		-	38	3.0	6.5	-	n.d.

* colour added
** not detectable

DISCUSSION OF RESULTS

Any commercial water purifier designed for the consumer market would probably find its use in the purification of extremely poor quality waters. For this reason, it was decided to assess the limitations and the performance of the Aquacare Water Purification System in the treatment of waters representing a wide range of water quality conditions.

Table 2 gives some of the water quality data and bacterial analyses collected from tests with tap water. It is noted that colour, temperature, turbidity and iron content in the water showed only very slight variations except where the colour was artificially intensified by the addition of brewed tea or iron chloride.

Data pertaining to the test runs with Humber River water are compiled in Table 3. The water shows a very wide range of conditions of colour, turbidity and temperatures reflecting the seasonal changes from July to January. The colour was found to vary from 5 to 100 Hazen units. The high levels of colour indicated for some of the test runs were due to the addition of brewed tea. The turbidity levels fluctuated from values ranging from 5 to 90 ppm SiO_2 and temperatures varied from 1.5 to 22.0^{o}C. Iron analysis were found to be constant except in those runs where ferric chloride was added.

The water analysis data presented in the tables, represent the water conditions at the time when the samples were collected for bacteriological analyses.

Performance of the Filter

The water drawn from the Humber River was found to be extremely turbid with the readings in the range of 25 to well over 100 ppm SiO_2. During the early part of this investigation, attempts were made to purify highly turbid water in the unit without any pretreatment. In most cases, it was found that when the turbidity levels in the river water exceeded 60 to 70 ppm SiO_2, the water could not be satisfactorily clarified. The turbid water caused the solenoid valve to close automatically and stop the flow to the UV sterilizer.

The filter did a remarkedly good job in clarifying the turbid water at 1.5 to 2.0 gpm, but when operated at higher flow rates, there was a breakthrough of turbid water and turbidity levels increased gradually in the filtered water. When the turbidity readings exceeded 30 ppm SiO_2, in the filtered water, the monitoring device activated the automatic shut-off valve and causing intermittent interruptions. Above flow rates of 3.5 to 4.0 gpm, the shut-off valve was usually completely closed.

Bactericidal Efficiency

The results of bacteriological tests performed on the samples collected during this study are presented in Tables 2, 3 and 4. These data show the bactericidal efficiency of the water purifier unit subjected to tests on waters under the stated conditions of water quality, temperature and flow rates. The efficiency of treatment can be determined by comparing the numbers of micro-organisms surviving in the treated water with the actual numbers that were present in untreated samples.

Table 2 gives the results of the experiments that were performed with tap water seeded with domestic sewage.

It can be seen that UV treatment was extremely effective in destroying all of the microorganisms belonging to the coliform and streptoccocus group in spite of the very high numbers that were present before treatment. This is exemplified in Run No. 4.

The results of tests with the Humber River water are reported in Table 3. The data indicated the coliform group of bacteria were completely destroyed at flow rates below 3.0 gpm in nearly all of the test runs. However, when the flow rate was increased above 3.0 gpm, some of the live bacteria begin to appear in the treated sample. There was also a corresponding increase in the level of turbidity at higher flow rates.

Table 4 gives a summary of bacterial results expressed in terms of total plate counts determined at 20°C. The data show the bactericidal efficiency of the unit indicated as "percent kill" by comparing the bacterial populations in the samples before and after UV irradiation. Other pertinent data related to the conditions of temperature and turbidity in the test water as well as the flow rates are tabulated to show whether these are significant factors in the effectiveness of UV treatment.

Although the bacterial results have demonstrated that the sterilizing capabilities of this unit were found to be over 99.9 percent efficient in samples with various levels of contamination, a complete sterilization was never attained. Similar observations have been cited in the literature by Fredette[21] and Stratford[23].

It was found that at higher flow rates, the number of surviving organisms began to increase along with a definite increase in turbidity. There is no doubt that turbidity was an important factor in the diminishing bactericidal effect of UV.

Effect of Colour and Turbidity

It is a well known fact that UV light has very limited penetrative powers in water. Small quantities of suspended solids and colloidal particles which impart turbidity and colour in water as well as some dissolved substances may interfere with the transmission of UV and reduce its germicidal effectiveness. In other words, disinfection of water by UV irradiation depends on the exposure of the microorganisms to adequate intensity of UV energy transmitted through the water. The presence of any impurities will tend to lessen the amount of UV transmitted in water and may also shield the organisms from radiation.

Gilcreas and DeLalla[14] studied the effects of colour and turbidity and determined their limiting values where no interference could be expected in the destruction of the coliform bacteria with a commercial UV water purifier. Similar experiments were conducted by Huff and his associates.[15] They reported that turbidity levels of 15 to 20 ppm SiO_2 decrease the intensity of UV below the design minimum whereas colour at a maximum level of 5 units or iron up to 3.7 ppm had shown no effect on the efficiency of treatment. However, they concluded that measurements of colour and turbidity were not necessarily good indicators to predict the decrease of UV transmission than can be expected in a given sample of water. Presence of other substances such as organic compounds have an appreciable effect on the absorption coefficient values of the water and therefore may interfere substantially with UV transmission.

Colour and turbidity were two factors considered in this investigation. It is rather difficult to point out the effects of turbidity on treatment efficiency in the experiments with tap water because the turbidity levels were all below 15 ppm SiO_2. The effects of turbidity seemed to be more obvious in the tests with the Humber River water. The least numbers of surviving organisms were found in samples with lower turbidity values; for example, in Runs No. 13 and 14. (Table 3) In Run No. 13, at the low flow rates when the turbidity was below 20 ppm SiO_2, a complete kill was achieved, but as the flow rates and turbidity began to increase, so did the numbers of live organisms.

The effects of colour on the germicidal efficiency can be seen in Runs No. 9 and 10 (Table 5) and Run No. 12 (Table 4). The results of bacteriological analyses show a definite increase in the numbers of surviving organisms remaining in the irradiated samples collected after the addition of colour.

Effects of Temperatures

Several references[10,12,14,18] have mentioned that the UV output from a germicidal lamp and hence its germicidal efficiency, can be reduced very markedly if there is a drop in the temperature due to the cooling effect of water surrounding the lamps. This happens when the cold water is allowed to come into direct contact with the UV lamp. However, in this study, the results of repeated tests with Humber River water at temperatures below 5.0°C showed that there was no apparent effect on the germicidal efficiency.

Virological Studies

The results of experiments to demonstrate the viricidal efficiency of UV are reported in Table 5. They show the effectiveness of UV irradiation on the inactivation of bacteriophages of E-coli B inoculated into the clean water in unusually large numbers and then passed through the Aquacare system at different flow rates. In addition, the results reveal the fate of viruses in natural surface water subjected to UV treatment.

Because no viruses were detectable in several of the untreated samples examined in Run No. 8, it was necessary to infuse a larger amount of culture in the test water during the subsequent runs.

In spite of the unusually high density of bacteriophages in Runs No. 9 and 10, the test data indicated that UV irradiation was extremely effective in virus inactivation as there were very low numbers of survivors remaining in all of the irradiated samples. Those obtained at low flow rates (1.5 gpm) had no survivors while all others had counts of less than 100 per 100 ml.

The addition of colour in the form of brewed tea had a very slight effect on the treatment efficiency. This can be seen in Runs No. 9 and 10.

The results of the tests with the Humber River water (Runs No. 11 and 13) showed that the UV was very effective in virus inactivation despite the conditions of relatively high turbidity. There were no viruses detected in any of the samples collected. However, it should be noted that initial virus populations in these samples were very low in comparison to those in the SEEDED tap water.

CONCLUSIONS

According to the information published in the literature and technical reports, water purification devices employing UV radiation are capable of purifying contaminated waters to meet the requirements of the drinking water standards provided that the water, prior to UV treatment, is reasonably free from any turbidity, light-absorbing substances or any other materials which may shield the microorganisms from radiation.

UV water purifiers offer several distinct advantages over chemical methods of disinfection. Most of these units are very simple and easy to operate once they have been set up. Most bacteria and pathogenic organisms can be completely inactivated with proper exposure to UV in a matter of seconds in contrast to a much longer period of time required with chemical methods. UV has been found to be particularly more effective in the treatment of some viruses than chlorination even at much higher dosages. This type of equipment requires very little attention during operation but there are no simple methods available, such as the orthotolidine test in chlorination, to check the thoroughness of UV treatment. Unlike chlorination, there is no danger of overtreatment as none of the constituents in the water will undergo chemical changes to cause taste and odour problems.

In spite of these advantages, UV radiation has not been proven very satisfactory for large water supplies because of its costs and uncertainty as a reliable method of disinfection.

At the present time, it appears that UV water purifiers could be utilized advantageously for the treatment of small individual water supplies where the water is relatively clear and where cost considerations are not too important.

The results of the evaluation tests on artificially contaminated tap water and natural river water indicated that the Aquacare Water Purification System consisting of a UV water purifier Model 300 and an auxiliary filter proved to be most effective in terms of bacterial disinfection when it was operated at approximately one-third of its stated flow capacity. Even though completely free of coliform bacteria, the treated water would not likely be accepted readily by the consumers for drinking purposes because of its poor clarity.

Although the automatic safety control system did take effect and shut off the water supply when the turbidity levels in the irradiated water had increased above 30 ppm SiO_2 it was found that the system could be operated without any difficulty to treat less turbid waters but the effluent was considered to be of dubious quality.

Treatment of waters in the system at higher flow rates had some adverse effects on the clarity and bacterial quality of the effluent believed to be caused by the breakthrough of turbid water in the filter.

Although it was possible to obtain a germicidal efficiency of over 99.9 percent in a number of samples with initial total plate counts at 20°C of 10^5 to 10^6 per 100 ml subjected to treatment in this system at various flow rates, a complete sterilization was never attained in any of the irradiated samples. The effectiveness of disinfection was dependent on the colour and turbidity of the water. At higher levels of turbidity, the numbers of surviving organisms in the waters increased significantly. However, the germicidal efficiency did not appear to diminish in any way when cold waters with temperatures as low as 1.0°C were treated.

UV irradiation with proper application appears to be one of the most effective and practical methods of inactivating any viruses present in water.

Aquacare Water Purification Systems with its patented tube cleaner and automatic monitoring device is probably one of the better UV water purifiers that have been developed commercially for the consumer market to disinfect small individual water supplies. However, when subjected to rigorous tests with raw water thought to be of poor quality, it failed to produce an effluent that could be considered acceptable for potable uses.

RECOMMENDATIONS

The application of UV water purification devices should be predicated by the availability of raw waters with reasonably good quality. They should be limited to the disinfection of water supplies where the raw water is relatively free from any colour and turbidity and any unusual changes in physical or chemical characteristics.

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